ULTRA HIGH ENERGY COSMIC RAYS: THE PRESENT POSITION AND THE NEED FOR MASS COMPOSITION MEASUREMENTS*

A A WATSON
School of Physics and Astronomy
University of Leeds
Leeds LS2 9JT, UK

The present situation with regard to experimental data on ultra high-energy cosmic rays is briefly reviewed. Whilst detailed knowledge of the shape of the energy spectrum is still lacking, it is clear that events above 10^{20} eV do exist. Evidence for clustering of the directions of some of the highest energy events remains controversial. Clearly, more data are needed and these will come from the southern branch of the Pierre Auger Observatory in the next few years. What is evident is that our knowledge of the mass composition of cosmic rays is deficient at all energies above 10^{18} eV. It must be improved if we are to discover the origin of the highest energy cosmic rays. The major part of the paper is concerned with this problem: it is argued that there is no compelling evidence to support the common assumption that cosmic rays of the highest energies are protons.

1. Motivation for Studying the Highest Energy Cosmic Rays

Efforts to discover the origin of the highest energy cosmic rays have been on going for many years. Since the recognition in 1966, by Greisen and by Zatsepin and Kuzmin, that protons with energies above 4×10^{19} eV would interact with the cosmic microwave radiation, there has been great interest in measuring the spectrum, arrival direction distribution and mass composition of ultra high-energy cosmic rays (UHECR). UHECR may be defined as those cosmic rays having energies above 10^{19} eV. Specifically, it was pointed out that if the sources of the highest energy protons were universally distributed, then there should be a sharp steepening of the energy spectrum in the range from 4 to 10×10^{19} eV. This predicted feature has become known as the GZK cut-off. If the UHECR were mainly Fe nuclei then there would also be a steepening of the spectrum. However, it is harder to predict this feature accurately as the relevant diffuse infrared photon field is poorly known: the steepening is expected to set in at higher energy.

*based on invited talk at 'Thinking, Observing and Mining the Universe', Sorrento Italy: 22 – 27 September 2003

Early instruments built to study this energy region (Volcano Ranch, Haverah Park, SUGAR and Yakutsk), were designed before the 1966 predictions and when the flux above 10^{19} eV was poorly known. Although of relatively small area (~ 10 km^2) sufficient exposure was accumulated to measure the rate of cosmic rays above 10^{19} eV accurately and to give the first indications that there might be cosmic rays with energies above 10^{20} eV. No convincing evidence of anisotropies above 10^{19} eV was established. It also became accepted that the problem of acceleration of protons and nuclei to such energies in known astrophysical sources is a major one. The projects that followed the pioneering ones also gave indications of trans-GZK particles but by the early 1990s it was apparent that even areas of 100 km^2, operated for many years, could not measure the properties of UHECR with adequate detail. Accordingley, work has started on a 3000 km^2 detector, the Pierre Auger Observatory.

2. The present observational situation

During the planning and construction of the Pierre Auger Observatory, observations continued with the Japanese array (AGASA) of plastic scintillators and the two fluorescence detectors (HiRes and Fly's Eye) of the University of Utah. The Japanese detector is an array of 111 x 2.2 m^2 plastic scintillators spread over 100 km^2. It will cease operation in December 2003 when an exposure of about 1600 km^2 sr years will have been made. Eleven events with energies above 10^{20} eV have been reported [1]. Spectra derived from arrays of particle detectors suffer from the difficulty that the energy of each primary cosmic ray must be inferred using models of particle physics interactions at energies well beyond those of present, or envisaged, accelerators. Thus, there is a systematic error in these energy assignments that is, inherently, unknowable. By contrast, the fluorescence method uses the scintillation light produced in the atmosphere by the secondary shower cascade and permits a calorimetric estimate of the energy in a manner familiar from accelerator experiments, although there are difficulties associated with the variable transmission properties of the atmosphere and with accurate knowledge of fluorescence yield. These instruments have also seen events with energies above 10^{20} eV but at a rate lower than that claimed by the Japanese group. Nevertheless, the highest energy event ever recorded (3×10^{20} eV) was detected by the Fly's Eye instrument and it is clear that there are cosmic rays above 10^{20} eV seen with both techniques and that the rate of such events is of order 1 per km^2 per steradian per century. A useful summary of the experimental situation is shown in figure 1.

Many questions remain about the detailed shape of the spectrum. The HiRes and AGASA spectra could be reconciled if the energy scale of one or other was adjusted by 30%. Moreover, the possibility that there are uncertainties in the flux measurements should not be overlooked. At the lower end of the AGASA spectrum the aperture is changing quite rapidly with energy [1] and uncertainties in the function that describes the fall-off of signal with distance may lead to uncertain-

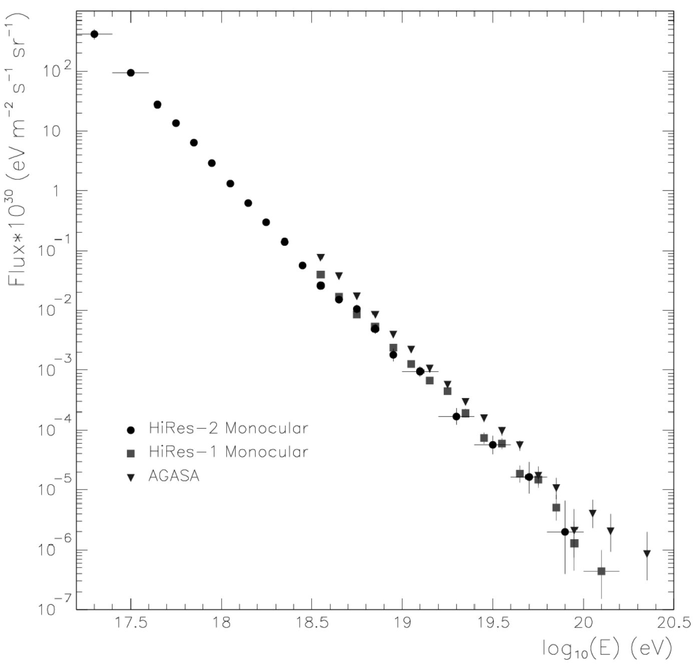

Figure 1. The energy spectra as reported by the AGASA[1] and HiRes[2] groups. This clear presentation of the spectra is due to D Bergman (University of Columbia).

ties in the aperture determination. At the highest energies, the AGASA aperture, limited by requiring that shower cores fall inside the array area, is known precisely. By contrast, with fluorescence detectors, the aperture continues to grow with energy. There is considerable uncertainly about the HiRes aperture, even in the case of stereo operation [2]. Further data are expected from the HiRes group and, in particular, from their period of stereo operation.

The situation concerning the arrival direction distribution of UHECR is not clear-cut either. For some time the AGASA group [3] have reported clustering on an angular scale of 2.5°, from a data set of 59 events above 4×10^{19} eV. The clusters are claimed to occur much more frequently than expected by chance with an estimate of 10^{-4} given for the chance probability. A preliminary search of the HiRes data [4] has not revealed clusters with the same frequency as claimed by AGASA.

Recently, Finley and Westerhoff [5] have presented an analysis using the directions of 72 events recently released by the AGASA group. They have taken the 30 events described in [6] as the trial data set and used the additional 42 events to search for pairs, adopting the criteria established by the AGASA group. Two pairs were found with a probability of 19% of occurring by chance.

It is clear that only further data will resolve the controversies over the energy

spectrum and over the clusters in arrival direction. The AGASA array will close at the end of 2003 when it will have achieved an exposure of ~ 1600 km^2 sr years. The HiRes instrument is expected to take data for another few years. The Pierre Auger Observatory has been designed to clarify the situation. It makes use of the ground array technique and of the fluorescence technique in what has become known as a 'hybrid detector'. When completed in late 2005, it will cover 3000 km^2 with 1600×10 m$^2 \times 1.2$ m deep water-Cherenkov detectors on a 1.5 km hexagonal grid. These detectors will be overlooked by four fluorescence detectors constructed on prominences at the edge of the area. An engineering array has operated for two years and all systems have performed within the design specifications [7]. While this observatory will mainly survey the Southern sky, it is expected to give a guide as to which of the spectra so far reported is correct and of the reality of clustering: the exposure made by the end of 2004 is expected to be comparable to that of AGASA. The immediate prospect, therefore, is for science data to be reported in mid-2005. This Southern part of the observatory is seen as the first of the two that are needed to provide full sky coverage.

3. Interpretation of the existing data

Many attempts have been made to explain the particles that exist beyond the GZK cut-off. If these are protons, the existence of such UHECR is seen as an enigma. They must come from nearby (at 10^{20} eV about 50% are expected from within 20 Mpc) and, adopting an extragalactic field of a few nanogauss, point sources would be expected to be detectable. However, none are seen and a wide variety of explanations has been offered. Amongst the many mechanisms proposed are the decay of topological defects or other massive relics of the big bang. Even more exotic is the suggestion of a violation of Lorentz invariance in such a manner that the energy-loss mechanism against the CMB is not effective, though acceleration remains an issue. If the primaries were iron nuclei then the situation would be slightly easier to understand. The higher charge would mean that acceleration could occur more readily and that bending, even in a weak magnetic field, would obscure the source directions. Without data on the mass composition it will be hard to draw conclusions about the origin of the particles, even when the spectral and clustering issues are clarified.

4. The mass of UHECR

Our knowledge about the mass of primary cosmic rays at energies above 10^{17} eV is rudimentary. Different methods of measuring the mass give different answers and the conclusions are usually dependent upon the model calculations that are assumed. Results from some of the techniques that have been used in attempts to assess the mass composition are now described and the conclusions drawn reviewed. Some of these techniques are applicable to the Pierre Auger Observatory.

4.1. *The Elongation Rate*

The elongation rate describes the rate of change of depth of shower maximum with primary energy. The term was introduced by Linsley [8] and, although his original conclusions have been largely superseded by the results of Monte Carlo studies, the concept is useful for organising data. A summary of measurements of the depth of maximum together with predictions from a variety of model calculations [9] is in figure 2. It is clear that if certain models are correct that one might infer that primaries above 10^{19} eV are dominantly protons; others suggest a mixed composition. The QGSJET set of models (basic QGSJET01 and the 5 options discussed in [9]) and the Sibyll 2.1 model force contrary conclusions.

4.2. *Fluctuations in Depth of Maximum*

A way to break this degeneracy has long been seen in the magnitude of fluctuations of the position of depth of maximum. If a group of showers with a narrow range of energies is selected then fluctuations about the mean X_{max} would be expected

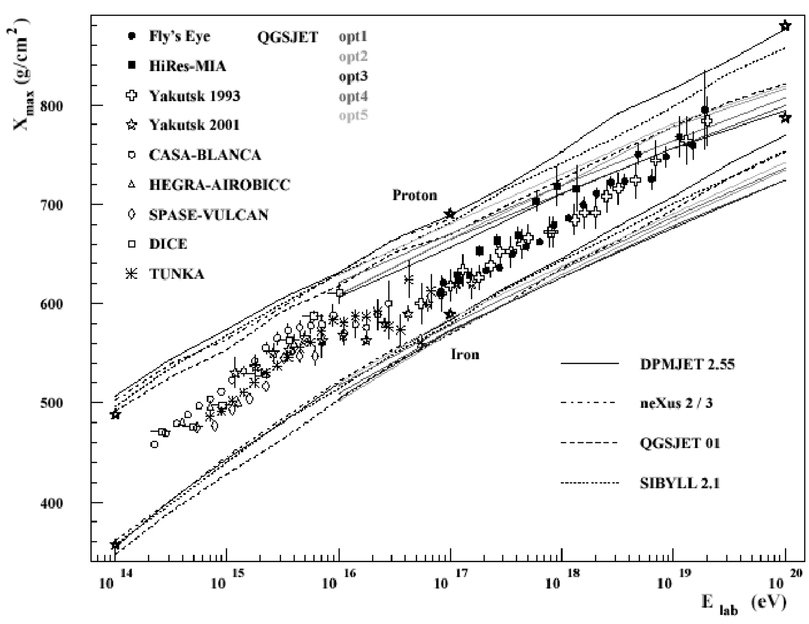

Figure 2. The depth of maximum, as predicted using various models, compared with measurements. The predictions of the five modifications of QGSJET[9] from which this diagram is taken, lie below the dashed line that indicates the predictions of QGSJET01.

to be larger for protons than for iron nuclei. A recent study of this, as reported

by the HiRes group [10], is shown in figure 3. These data are for 553 events $> 10^{18}$ eV. It is argued that the fluctuations are so large that a large fraction of protons

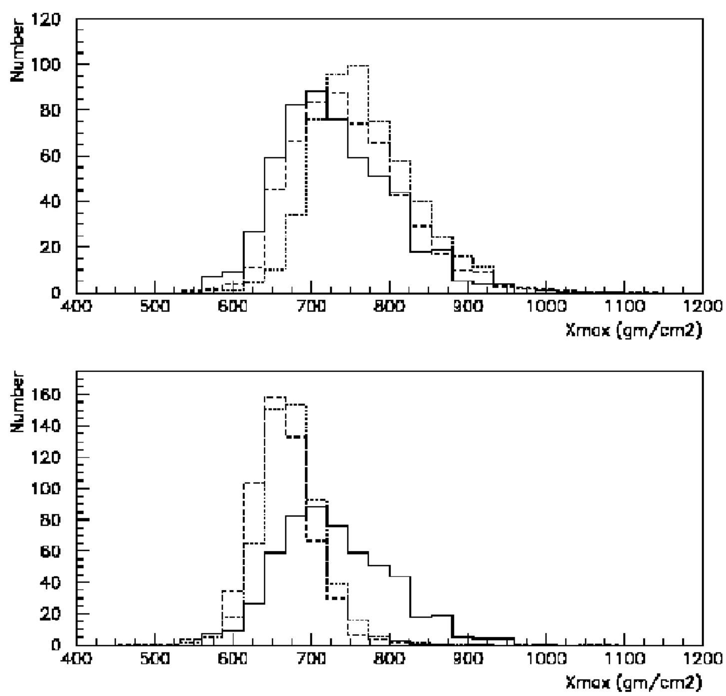

Figure 3. The HiRes data [10] on X_{max} for $> 10^{18}$eV. The solid lines in the two figures are the experimental data. The upper figure shows predictions for proton primaries for the QGSJET and Sibyll models. Predictions for iron primaries are shown in the lower figure.

is indicated. However, the HiRes data have been analysed assuming a standard US atmosphere for each event. It is probable that the atmosphere deviates from the standard conditions from night to night, a view strengthened by the results of balloon flights made from Malargüe [11]. These have shown that the atmosphere changes in a significant way from night to night, and from summer to winter. If a standard atmosphere is used, some of the fluctuations observed in X_{max} may be incorrectly attributed to shower, rather than to atmospheric, variations. Thus, it may be premature to draw conclusions about the presence of protons from this, and similar earlier analyses.

4.3. *Mass from muon density measurements*

A shower produced by an iron nucleus will contain a larger fraction of muons at the observation level than a shower of the same energy created by a proton. Many efforts to uncover the mass spectrum of cosmic rays have attempted to use this fact. However, although the differences are predicted to be large (~70% more muons in an iron event than a proton event), there are large fluctuations and, again, there are differences between what is predicted by particular models. Thus, more muons are predicted with the QGSJET set than with the Sibyll family. The difference arise from different predictions as to the pion multiplicities in nucleon-nucleus and pion-nucleus collisions [12]. Recent data from the AGASA group [13] is shown in figure 4. There are 129 events above 10^{19} eV, of which 19 have energies $> 3 \times 10^{19}$ eV. Measurements at distances between 800 and 1600 m were used to derive the muon density at 1000 m with an average accuracy of 40%. These muon densities are compared with the predictions of model calculations. It is clear that the difference between the proton and iron predictions is small, especially when fluctuations are considered. The AGASA group conclude that at 10^{19} eV the fraction of Fe nuclei is 14^{+16}_{-14}% and above 3×10^{19} eV it is 30^{+7}_{-6}%. Of the 5 events above 10^{20} eV, 3 are as well fitted by iron nuclei as by protons.

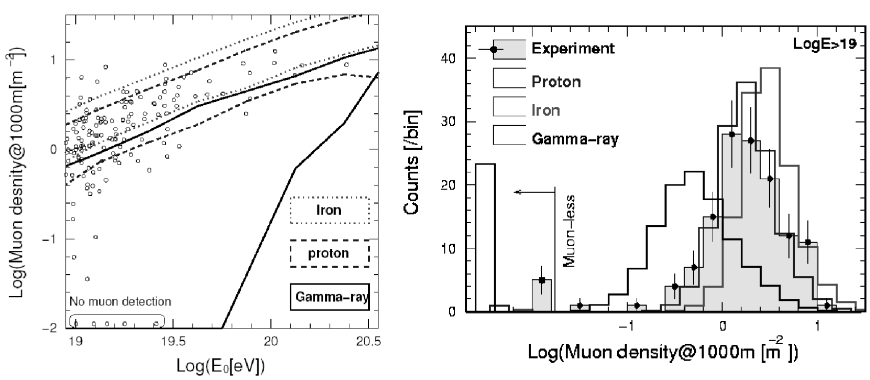

Figure 4. The muon density at 1000 m as measured at AGASA [13]. In the left hand diagram, the dotted lines are the predictions for iron nuclei, the dashed lines for protons and the solid lines for photons. In the right hand diagram, the shaded histogram represents the data with predictions for iron, protons and photons shown by the line histograms: iron is the right-most histogram.

The conclusions are sensitive to the model used and as the Sibyll model predicts fewer muons than the QGSJET model, higher iron fractions would have been inferred had that model been adopted.

At lower energies, there are muon data from the Akeno array and from AGASA [14]. Different analyses have been made. The AGASA group[14] claim that the

measurements are consistent with a mass composition that is unchanging between 10^{18} and 10^{19} eV. Dawson et al. [15], in an effort to reconcile these data with earlier fluorescence results have argued that, with a different model, the mean mass is lower at higher energies. In the context of the present discussion, it is worth noting that $50-60\%$ of iron, near 10^{19} eV, is quite consistent with both the AGASA and Akeno data for a range of models and with efforts to account for systematic uncertainties. It might be productive to re-examine these data using the latest QGSJET and Sibyll models.

4.4. *Mass estimates from the lateral distribution function*

The rate of fall of particle density with distance from the shower axis provides another parameter that can be used to extract the mass composition. Showers with steeper lateral distribution functions (LDFs) than average will arise from showers that develop later in the atmosphere, and vice versa. A detailed measurement of the LDFs of showers produced by primaries of energy greater than 10^{17} eV was made at Haverah Park using a specially constructed 'infilled array' in which 30 additional water tanks of 1 m^2 were added on a grid with spacing of 150 m. When the work was completed in 1978, the data could not be fitted with the shower models then available. Recently [16], the data have been re-examined using the QGSjet98 model.

The appropriateness of this model was established by showing that it adequately described data on the time spread of the Haverah Park detector signal over a range of zenith angles and distances near the core (<500 m). Here the difference predicted between the average proton and iron shower is only a few nanoseconds and the fit is good. Densities were fitted by $\rho(\mathrm{r}) \sim \mathrm{r}^{-(\eta+r/4000)}$, where η is the steepness parameter. The spread of η is compared with predictions in figure 5. The proton fraction, assuming a proton-iron mixture, is found to be independent of energy in the range 3×10^{17} to 10^{18} eV and is (34 ± 2) %. If this is evaluated with QGSJET01, in which a different treatment of diffractive processes is adopted, then the fraction increases to 48%. It is larger because the later model predicts shower maxima that are higher in the atmosphere and accordingly, to match the observed fluctuations, the proton fraction must be increased. The deduced ratio thus has a systematic uncertainty from the models that is larger than the statistical uncertainty. Although the necessary analysis has not been made, it is clear that the Sibyll 2.1 model would require a smaller fraction of protons.

A similar analysis has been carried out using data from the Volcano Ranch array. As with the Haverah Park information, no satisfactory interpretative analysis was possible when the measurements were made. With QGSJET01, the fraction of protons is estimated as $(25 \pm 5\%)$ between 5 and 10×10^{18} eV [17].

4.5. *Mass from the thickness of the shower disk*

The particles in the shower disc do not arrive at a detector simultaneously. The arrival times are spread out because of geometrical effects, velocity differences, mul-

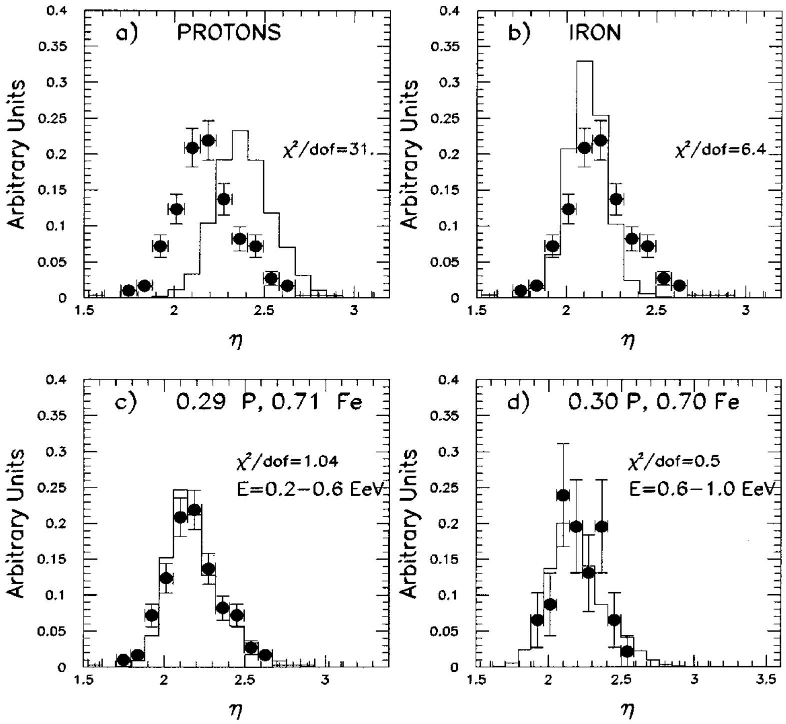

Figure 5. The experimental measurements of the steepness parameter, η, compared with predictions made using the QGSJET98 model assuming different mass mixtures [16]. The lower set of diagrams illustrates the insensitivity of the mass mixture to energy.

tiple scattering and geomagnetic deflections. The first particles to arrive (except very close to the shower axis) are the muons: they are scattered little and geometrical effects dominate. At Haverah Park four detectors, each of 34 m^2, provided a useful tool for studying the thickness of the shower disc, which depends upon the development of the cascade. Recently, an analysis of 100 events has shown that the magnitude of the risetime is indicative of a large fraction ($\sim$80%) iron nuclei at $\sim 10^{19}$eV [18]. This type of study will be considerably extended with the Pierre Auger Observatory, in which each water tank is equipped with 25 ns flash ADCs [19].

4.6. *Limits to the fraction of photon primaries*

It is unlikely that the majority of the events claimed to be near 10^{20} eV have photons as parents as some of the showers seem to have normal numbers of muons (the tracers of primaries that are baryonic), figure 4. Furthermore, the cascade profile of the most energetic fluorescence [20] event is inconsistent with that of a photon [21]. This approach can be used when specific shower profiles are available. An alternative

method of searching for photons has recently been developed using showers incident at very large zenith angles. Deep-water tanks have a good response to such events out to beyond 80°. At such angles the bulk of the showers detected are created by baryonic primaries but are distinctive in that the electromagnetic cascade stemming from neutral pions has been completely suppressed by the extra atmosphere. At 80° the atmospheric thickness to be penetrated is ~ 5.7 atmospheres. At Haverah Park, such large zenith angle showers were observed and the shower disc was found to have a very small time spread. A complication for the study of inclined showers is that the muons, in their long traversal of the atmosphere, are significantly bent by the geomagnetic field. A detailed study of this has been made and it has been shown that the rate of triggering of the Haverah Park array at large angles can be predicted [22]. In addition, it was shown that the energy of the primaries could be estimated with reasonable precision and an energy spectrum derived. The concept of using the known, and mass independent, spectrum deduced by the fluorescence detectors to predict the triggering rate as a function of the mass of the primary has led to a demonstration that the photon flux at 10^{19} eV is less than 40% of the baryonic component [23]. In addition to this novel approach, a more traditional attack on the problem by the AGASA group, searching for showers which have significantly fewer muons than normal, has given the same result [24]. These experimental limits are in contrast to the predictions of large photon fluxes from the decay of super-heavy relic particles, one of the exotic candidates that have been invoked to explain the enigma [25].

A first attempt at estimating the photon flux at 10^{20} eV can be made from the data of figure 4 and other observations. In addition to the Fly's Eye event discussed in [18], the HiRes group has reported one stereo event [26] that is nearly as large and with a longitudinal development profile that does not match that of a photon. At least one of the very inclined events in the study of [23] is above 10^{20} eV and the Yakutsk event [27] of 57° is very rich in muons. There are thus 9 events above 10^{20} eV for which a judgement about their photonic nature can be made. If none of the 5 AGASA events above 10^{20} eV shown in figure 4 is a photon, then the 95% confidence limit for the photon flux, as a fraction of the total cosmic ray flux, is 33%. If two of the AGASA events are produced by photons, then the flux is estimated as (22^{+30}_{-14}%). Both figures are of interest in the context of the super-heavy relic models [25]. Further details will be given elsewhere [28].

Conclusions

The question of spectral shape of the UHECRs remains uncertain and, along with the issue of the clustering of the arrival directions, may only be resolved by the operation of the Pierre Auger Observatory. To make full use of this forthcoming information, it is necessary to improve our knowledge of the mass of the cosmic rays above 10^{19} eV. Such evidence as there is does not support the common assumption that all of these cosmic rays are protons: there may be a substantial fraction of iron

nuclei present. Photons do not appear to dominate at the highest energies.

Acknowledgements

I would like to thank the organisers for inviting me to the Sorrento meeting and, in particular, Michelangelo Ambrosio for his hospitality. Work on UHECR at the University of Leeds is supported by PPARC, UK.

References

1. Takeda, M., et al., Astroparticle Physics 19 447 2003 and astro-ph/0209442
2. Bergman, E., et al., Proc 28th Int Cos Ray Conf (Tsukuba) 1 397 2003
3. Teshima, M., et al., Proc 28th Int Cos Ray Conf (Tsukuba) 1 437 2003
4. Finley, C. B., et al., Proc 28th Int Cos Ray Conf (Tsukuba) 1 433 2003
5. Finley, C.B., and S Westerhoff, astro-ph/0303484, submitted to Astroparticle Physics
6. Hayashida, N., et al., ApJ 522 225 1999
7. Auger Collaboration: Abraham, J., et al., NIM A, November 2003 (in press)
8. Linsley J., Proc 15th Int Cos Ray Conf (Plovdiv) 12 89 (1977)
9. Zha, M., J Knapp and S Ostapchenko, Proc 28th Int Cos Ray Conf (Tsukuba) 2 515 2003
10. Archbold, G., et al., Proc 28th Int Cos Ray Conf (Tsukuba) 1 405 2003
11. Keilhauer, B., et al., Proc 28th Int Cos Ray Conf (Tsukuba) 2 879 2003
12. Alvarez-Muñiz, J., et al., Phys. Rev. D66 033011 2002 and astro-ph/0205302 2002
13. Shinosaki, K., et al., Proc 28th Int Cos Ray Conf (Tsukuba) 1 401 2003
14. Hayashida, N., et al., J Phys G 21 1101 1995
15. Dawson, B.R., R Meyhandan and K M Simpson, Astroparticle Physics 9 331 1998
16. Ave, M., et al., Astroparticle Physics 19 61 2003 and astro-ph/0203150
17. Dova, M. T., et al., Proc 28th Int Cos Ray Conf (Tsukuba) 1 377 2003 and Astparticle Physics (in press)
18. Ave, M., et al., Proc 28th Int Cos Ray Conf (Tsukuba) 1 349 2003 (and in preparation)
19. Dova, M.T., for the Pierre Auger Collaboration Proc 28th Int Cos Ray Conf (Tsukuba) 1 369 2003
20. Bird, D.J., et al., Phys Rev Letters 71 3401 1993
21. Halzen, F., et al., Astroparticle Physics 3 151 1995
22. Ave, M., et al., Astroparticle Physics 14 109 2000 and astro-ph/0003011
23. Ave, M., et al., Phys Rev Letters 85 2244 2000 and astro-ph/0007386
24. Shinosaki, K., et al., Astrophysical Journal 571 L117 2002
25. Berezinsky, V., Kachelreiss, M. and Vilenkin, A., Phys Rev Letters 22 4302 1997, Benakli, K., Ellis, J. and Nanopolous, D.V., Phys Rev D59 047301 1999, Birkel, M and Sarkar, S., Astroparticle Physics, 9, 297 1998, Chisholm, J.R. and E W Kolb, astro-ph/0306288, submitted to Phys Rev D, Chung, D J H., E W Kolb and A Riotto, Phys Rev Letters 81 4048 1998, Rubin, N. A., M Phil Thesis, University of Cambridge, 1999, Sarkar, S., and Toldra, R., Nuclear Physics B 621 495 2002
26. Loh, G., NEEDS Workshop, Karlsruhe 2002, www-ik.fzk.de/∼needs/needs/loh.pdf
27. Efimov, N.N. et al., Proceedings of the ICCR International Symposium (Kofu): Astrophysical Aspects of the Most Energetic Cosmic rays, World Scientific (editors: M Nagano and F Takahara) p 20 1990
28. Dova, M.T. and A A Watson, in preparation